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Aging and the visual perception of rigid and nonrigid motion

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Nonrigid forms of motion are commonplace in everyday life. Given previously documented age-related deteriorations in various tasks involving motion (discriminating speed, identifying motion direction, etc.), an experiment was conducted to evaluate the potential effect of age upon the visual ability to detect rigid and nonrigid object motion. Thirty younger and older observers participated in the experiment (mean ages were 19.9 and 75.8 years, respectively). As has been done multiple times in the past, the individual motions of object vertices were manipulated to simulate either rigid motion (rotation in depth, with or without precession) or two different types of nonrigid motion (also rotation in depth with or without precession, but with added object deformation). In confirmation of previous research, there were large effects of nonrigid motion type and precession upon the ability to differentiate between rigid and nonrigid object motion. There was also a large effect of age, such that the discrimination performance of the younger observers was 49.6% higher than that exhibited by the older observers. In this first ever study of aging and nonrigid object motion perception, we thus find that aging is associated with a substantial impairment in the ability to visually perceive object nonrigidity.

In the natural world, the world in which the mammalian visual system evolved, nonrigid motions almost certainly occur more frequently than rigid motions. Tree branches and tall grasses bend in the wind, birds and butterflies fly (flap their wings), fish and manta rays swim (fins wave and bodies undulate as fish and mantas propel themselves through the water), while terrestrial mammals walk, run, and climb. Clouds deform, waves move through lake and ocean surfaces, and rivers flow. Nonrigid motion is ever present in everyday life, but the visual perception of nonrigid motion has received relatively little attention, with the exception of biological motion[1–5]. Fortunately, a number of studies have been conducted to investigate the perception of elastic bending, stretching, and object deformation[6–10]. A thorough study by Todd[11] of the visual perception of nonrigid motion is now more than 40 years old. He found that some varieties of nonrigid object motion are much more detectable to human vision than others.

A number of very important visual abilities, such as the perception of static object shape and distance, are well maintained with age[12–14]. In contrast, aging is accompanied by many deficits involving motion. Examples of such age-related impairments would include (1) the perception of speed[15–17], (2) the perception of motion direction[5,18–22], and (3) the perception of 3-D shape from motion[23–26]. An excellent review of the literature regarding motion perception and aging has been recently published by Billino and Pilz[27]. A quick review of this literature would probably produce the impression that there is a significant decline in all motion-related visual abilities with increasing age. Such a conclusion, however, would be erroneous and misleading. With regards to the perception of motion direction, there are circumstances in which older adults perform better than younger adults[28,29]. From the results of their study, Betts, Taylor, Sekuler, and Bennett[28] concluded (p. 361) that "aging alters such center-surround interactions in ways that improve performance in some tasks. We found that older observers required briefer stimulus durations than did younger observers to extract information about stimulus direction in conditions using large, high-contrast patterns". In another study requiring judgments of motion direction, Hutchinson, Ledgeway, and Allen[30] found (p. 1) that “with the smallest apertures tested, young participants’ motion coherence thresholds were considerably higher (~1.5 times worse) than those of their older counterparts. Therefore, when RDK size is relatively small, older participants were actually better than young participants at processing global motion". Older adults also often perform well for judgments involving biological motion[4,5]. For example, Norman et al.[4] found that the performance of older and younger adults for biological motion discrimination was essentially identical for longer stimulus durations of 400 msec. Two studies[5,22] have also found that the visual perception of heading from optic flow was unaffected by aging.

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Billino et al.[5] summarized their results (p. 1258) by saying "radial flow strikingly differed from both other motion types in that perceptual thresholds were not affected by age." In the discussion of their results, Billino et al.[5] speculated (p. 1260) that "motion types with high ecological relevance, e.g., radial flow or biological motion, are processed especially efficiently and are therefore less affected by age-related decline". Given the high frequency of occurrence of nonrigid motion in everyday natural environments (as described in the first paragraph of this introduction), one might therefore expect that nonrigid motion detection would be less affected by age than many other motion-related tasks.

The purpose of the current experiment is straightforward—to utilize reliable techniques used in past research on younger adults (graduate student participants) to investigate whether older adults can effectively perceive nonrigid object motion (and distinguish it from rigid motion). Given the well known age-related deficits that exist for many other tasks involving motion, it is certainly possible that such deficits would also occur for nonrigid motion perception. It is just as likely, however, that the ability to perceive nonrigid motion may be robust to the effects of aging given the widespread presence (in both the dorsal and ventral visual streams of information flow in extrastriate visual cortex) of specialized neuronal networks that exhibit a preference for nonrigid motion[31]. Also remember that biological motion perception (a form of nonrigid motion)[4,5] is relatively well preserved in older adults. It is certainly possible that the relatively good performance obtained for older adults when judging biological motion might extend to other forms of nonrigid motion, such as those investigated in the current study.

Method

Apparatus

An Apple Mac Pro computer (Quad-Core Intel Xeon processor, with ATI Radeon HD 5770 hardware-accelerated graphics) was used to present the apparent motion sequences and to record the observers' responses. The stimulus displays were presented on an Apple 27-inch LED Cinema Display, and were viewed from a distance of 100 cm. The observers viewed the stimuli monocularly with a viewing hood that has been used previously[25,26].

Experimental stimuli

The experimental stimuli were essentially identical to a subset of those previously used by Todd[11] in his seminal investigation of nonrigid motion perception (also see similar manipulations in Experiment 2 of Perotti, Todd, & Norman[32]). The simulated objects were wireframe 3-D figures, similar to the classic stimulus objects used by Wallach and O'Connell[33], Green[34], and Todd, Akerstrom, Reichel, and Hayes[35]. On each trial, the simulated 3-D structure and motion of our wireframe objects was defined by the motions of eight randomly positioned vertices, thus each 3-D object was composed of seven connected line segments. Static examples of two such stimulus objects are shown in Fig. 1.

The particular rigid and nonrigid object motions used by Todd[11] and in the current experiment were created as follows. It is important to remember that rotation of a 3-D point in depth (in general) produces an elliptical trajectory in a projected image, for example, at the eye (see Todd[11] & p. 58 of Braunstein[36]). The trajectories of

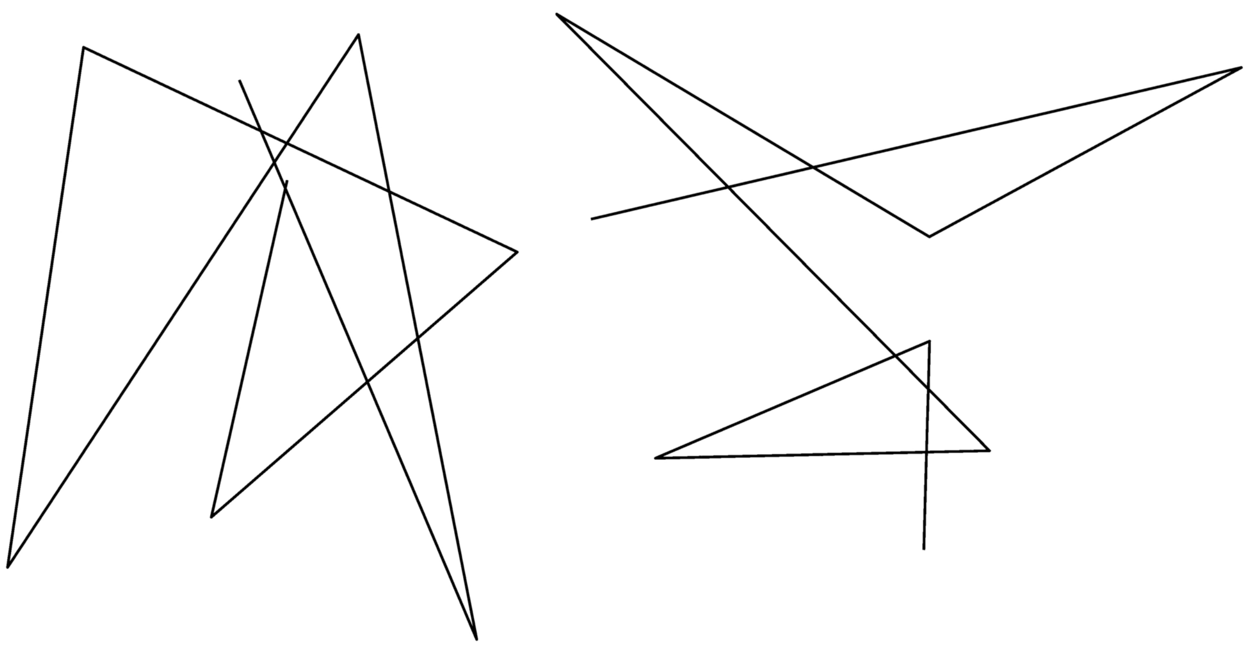

Fig. 1. Two static snapshots of representative wireframe stimulus objects. Each object was defined by the motions of eight interconnected vertices (seven connected line segments). It is important to keep in mind that the actual stimulus displays appeared 3-dimensional, where the 3-D structure was defined by motion (see Todd[11], Todd, Akerstrom, Reichel, & Hayes[35], Wallach & O'Connell[33], & Green[34]).

object points produced by rigid rotation of the object in depth all have the same elliptical shape (eccentricity) and orientation; an example of such trajectories is shown in the upper left panel of Fig. 2. Examples of two of the nonrigid object motions studied by Todd[11] are shown in the upper right and lower panels of Fig. 2. The trajectories of the object points in the upper right panel are clearly inconsistent with rigid object motion, because the trajectories of the object's constituent points have different orientations. The trajectories shown in the lower panel are inconsistent with rigid object motion, because the trajectories of the object's constituent points have different eccentricities. These are the two types of nonrigid object motion used in the present investigation; they were chosen, because Todd[11] found that at least for younger observers (graduate students), the nonrigidity associated with different trajectory orientation was relatively easy to see/detect, whereas the nonrigidity associated with different trajectory eccentricity was difficult to detect.

The image motions (trajectories) of the stimulus objects' constituent points in the current experiment were generated in an identical manner to that used in the pioneering study by Todd[11]. In particular, the final X and Y coordinates of each point were generated according to the following equations:

$$X1 = A\cos(\omega t + \alpha)$$

$$Y1 = \varepsilon A\sin(\omega t + \alpha)$$

$$X2 = X1\cos(\theta) + Y1\sin(\theta) + B$$

$$Y2 = Y1\cos(\theta) - X1\sin(\theta) + C$$

$$X = X2\cos(\phi t) + Y2\sin(\phi t)$$

$$Y = Y2\cos(\phi t) - X2\sin(\phi t)$$

where X1, Y1, X2, and Y2 are internal variables used only for temporary storage of the results of interim calculations (i.e., are dummy variables). The remaining parameters control the motions of the object vertices and determine whether the resulting stimulus motions simulate either rigid object rotation in depth (upper left panel of Fig. 2) or one of the two nonrigid types of motion used in the experiment (upper right and lower panels of Fig. 2). The parameter ω controls the frequency of the movement around the elliptical trajectories, while θ determines the orientation of each trajectory in the image. The parameter ε manipulates the eccentricity of the elliptical trajectories, whereas A controls the amplitude (i.e., width) of the trajectory. Parameters B and C determine the x and y intercepts of the trajectories. Finally, α sets the phase of each object point around its elliptical trajectory at the beginning of the stimulus display and ϕ determines the amount/magnitude of any precession. In his investigation, Todd[11] found that adding precession (rotation in the image plane) to the basic stimulus types (the three types of object motion shown in Fig. 2) made it much more difficult for his younger observers to discriminate rigid from nonrigid motion (see Table 1 of Todd[11]).

The values of the parameters used to generate the stimulus displays in the current experiment were usually identical or highly similar to those used by Todd[11]). Two exceptions are the parameters A and C. Because our display screen (Apple 27-inch LED Cinema Display) was much larger than the Tektronix CRT (cathode ray tube) used by Todd[11], the values of A and C were about twice as large as those he used. Each trajectory in our stimulus objects had values of A (unit is cm) chosen from this set {3.0, 3.34, 3.68, 4.02, 4.36, 4.7, 5.04, 5.38, 5.72, 6.06}. One can see these variations in amplitude/width of the trajectories in all panels of Fig. 2. Each trajectory in our stimulus objects had values of C (unit is cm) chosen from this set {−6.3, −4.9, −3.5, −2.1, −0.7, +0.7, +2.1, +3.5, +4.9, +6.3}. One can also see these variations in trajectory height (from the center of the display screen) in all three panels of Fig. 2. The parameter α (angle, in degrees) for each trajectory took a value from this set {36, 72, 108, 144, …, 360}. As in the study by Todd[11], the parameters A, C, and α were chosen at random without replacement. Because we did not use all of the types of nonrigidity studied by Todd[11], the value of B was always set to zero. For the rigid motions and nonrigid motions with different trajectory orientation, the parameter ε was always set to 0.375; for the nonrigid motions with different trajectory eccentricity, each trajectory received a different eccentricity with ε values being chosen from this set {0.0, 0.11, 0.22, 0.33, 0.44, 0.55, 0.66, 0.77}. These similarities and differences in trajectory eccentricity can be seen in the three panels of Fig. 2. For the rigid motions and nonrigid motions with different trajectory eccentricity, the parameter θ was always set to zero (orientation of major axis of elliptical trajectories was horizontal); for the nonrigid motions with different trajectory orientation, each trajectory possessed a different orientation with θ values (degrees) being chosen from this set {0, 19, 38, 57, 76, 95, 114, 133}.

To create the animation and produce the apparent motion sequences, t (time) was varied from 1 to 180 (180 frames in the motion sequences); given that ω was 4.0°, the object vertices made two complete rotations in depth (4.0 * 180 = 720° = 2 revolutions). The frame update rate was 60 Hz, thus the duration of each apparent motion sequence was 3.0 s. For the stimuli with added precession (rotation in the image plane as well as object rotation in depth), the magnitude of ϕ was set to 4.0° (the same as ω). Representative apparent motion sequences without precession for rigid motion, nonrigid motion due to different trajectory orientation, and nonrigid motion due to different trajectory eccentricity are shown (as Supplementary Information) in Supplementary Videos 1, 2, and 3, respectively. Representative apparent motion sequences with precession for rigid motion, nonrigid motion due to different trajectory orientation, and nonrigid motion due to different trajectory eccentricity are shown in the Supplementary Information as Supplementary Videos 4, 5, and 6, respectively.

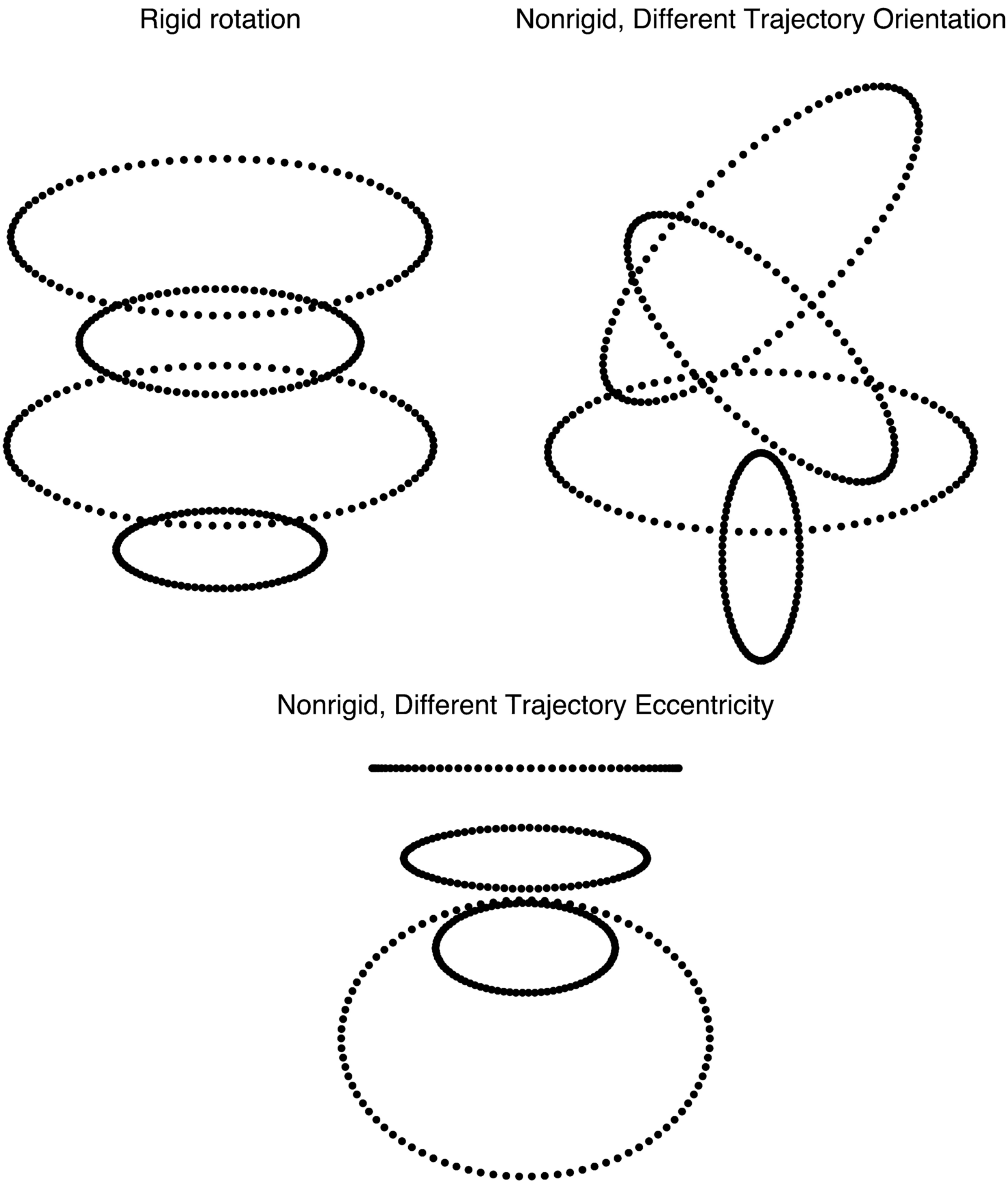

Fig. 2. Example trajectories illustrating the three types of object motion used in the experiment. Each panel in this figure plots the motions of four representative object points; it is important to keep in mind that the actual stimulus objects had twice as many vertices (8). Simulated rigid object rotation in depth is depicted in the upper left panel. Note that all of the elliptical trajectories have the same shape and orientation. The nonrigid object motions are illustrated in the upper right and bottom panels. One type of nonrigidity is inconsistent with rigid object motion, because the elliptical trajectories of the object's constituent points have different orientations (upper right panel). The other type of nonrigidity is inconsistent with rigid object motion, because the elliptical trajectories of the object's constituent points have different eccentricities (bottom panel). The three motion types represent a subset of those investigated by Todd[11].

Procedure

The observers were familiarized with the stimuli and task in multiple ways. The observers were shown physical 3-D "wireframe" figures constructed from PVC (polyvinyl chloride) pipe (see Fig. 3). Such rigid figures were rotated in depth to demonstrate rigid object rotation. Rotation in the frontoparallel plane was also demonstrated with the figure to illustrate precession. A similar configuration of PVC pipe, where adjacent segments of pipe were connected by universal joints (and thus the joints of the wireframe figure were not rigid and each length segment was free to move in any direction), was used to illustrate nonrigid 3-D deformation. Following the familiarization with physical rigid and nonrigid motion, the observers participated in a block of about 20 trials with the computer-generated stimuli (see experimental stimuli section and Fig. 2) prior to beginning the actual experiment. The experiment did not begin until the stimulus types and task (judge whether each stimulus depicted rigid or nonrigid motion) were absolutely clear.

The observers completed two blocks of trials (75 trials each) and therefore made a total of 150 judgments. One block was devoted to stimulus motions that included precession (rotation in the image plane) in addition to simulated object rotation in depth, while the other block did not incorporate precession. The order of the experimental blocks was counterbalanced across the observers so that half of the observers judged stimuli with precession first, while the remaining half judged stimuli without precession first. Within each block, each of the three motion types (rigid, nonrigid with different trajectory orientation, & nonrigid with different trajectory eccentricity, see Fig. 2) was presented 25 times, all in a completely random order. The 3-D wireframe objects themselves were different and randomly shaped on every trial (see examples in Fig. 1). The observers' task, as described above, was straightforward, simply to indicate whether each stimulus object's motion was rigid or nonrigid. No feedback regarding performance was ever given during the experimental trials.

Observers

If an age-related deficit does exist with regards to the detection of rigid and nonrigid motion of 3-D objects and if it is as large as the age effect found in a recent experiment of ours (see Experiment 1 of Norman et al.[37]) involving the perception of 3-D shape from motion, a power analysis reveals that we would need a total of 20 observers (10 younger adults & 10 older adults) to have a 95% chance of detecting it (at standard significance levels of $p < 0.05$). Being conservative and wanting to be confident of an adequate sample size, we recruited a total of 30 observers to participate (15 younger & 15 older). The mean ages of the younger and older observers were 19.9 years (ages ranged from 18 to 22 years, sd = 1.4) and 75.8 years (ages ranged from 67 to 83 years, sd = 4.3), respectively. Two of the 15 younger observers were undergraduate student coauthors (ABR & AMB). For unknown reasons, one potential older observer (75 years old) was unable to perform the task at better than chance levels, and he was therefore excluded. The observers had excellent visual acuity: the acuity of the younger and older observers measured at 100 cm was −0.10 and −0.01 LogMAR (log minimum angle of resolution), respectively (zero LogMAR represents normal visual acuity, while positive and negative values represent worse than and better than normal acuity, respectively). The study was approved by the Institutional Review Board of

Fig. 3. A rigid 3-D configuration of PVC pipe used to familiarize the observers with the experimental stimuli and task.

Western Kentucky University, and each observer signed an informed consent document prior to testing. Our research was carried out in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

Results

Various aspects of the results are shown in Figs. 4 through 8. We first evaluated the observers' ability to distinguish between rigid and nonrigid motion in terms of d' (Fig. 4), the perceptual sensitivity measure of signal detection theory[38,39]. The observers' ability to discriminate between rigid and nonrigid motion depended strongly upon the type of nonrigidity (different trajectory orientation versus different trajectory eccentricity, $F(1, 28) = 338.0$, $p < 0.000001$; $\eta^2_p = 0.92$), as indicated by a 2 (age) × 2 (type of nonrigidity) × 2 (precession) split-plot analysis of variance (ANOVA). There was also a large effect of precession ($F(1, 28) = 144.7$, $p < 0.000001$; $\eta^2_p = 0.84$). The interaction between type of nonrigidity and precession was also significant ($F(1, 28) = 25.0$, $p < 0.0001$; $\eta^2_p = 0.47$), such that the effects of precession were larger when distinguishing between rigid motion and nonrigid motion with different trajectory orientation than when distinguishing between rigid motion and nonrigid motion with different trajectory eccentricity. These effects of type of nonrigidity, precession, and their interaction are all clearly visible in Fig. 4.

The results of the experiment also revealed a variety of effects involving age upon d'. First, the main effect of age was significant ($F(1, 28) = 11.4$, $p = 0.002$; $\eta^2_p = 0.29$), such that the younger observers' d' values were 49.6% higher than those of the older observers (average d' values were 1.928 and 1.289, respectively). The age × type of nonrigidity and age × precession interactions were also both significant (age × type of nonrigidity: $F(1, 28) = 9.6$, $p = 0.004$; $\eta^2_p = 0.25$; age × precession: $F(1, 28) = 6.9$, $p = 0.014$; $\eta^2_p = 0.20$). The 3-way interaction, however, was not significant ($F(1, 28) = 2.6$, $p = 0.12$; $\eta^2_p = 0.08$). Both of the significant 2-way interactions involving age are visible in Fig. 4. The effect of the type of nonrigidity was larger in magnitude for the younger observers than the older observers. The effect of precession was also larger for the younger observers.

The overall effect of age upon discrimination performance (d') could be due to the younger observers having a higher hit rate (than the older observers), a lower false alarm rate, or both[38,39]. In the current context a hit occurred when the stimulus was rigid and an observer correctly responded that it was rigid, whereas a false alarm occurred when a nonrigidly moving stimulus was presented, but an observer incorrectly indicated that it was rigid (a miss happened when the stimulus was rigid but an observer failed to detect that it was rigid and responded "nonrigid", while a correct rejection occurred when a stimulus was nonrigid and an observer correctly responded that it was nonrigid). In defining the hit and false alarm rates, we followed the same convention as Braunstein, Hoffman, and Pollick[40]. The observers' hit rates and false alarm rates are shown in Figs. 5 and 6, respectively. With regards to hit rates, the main effects for both age and precession were significant (age: $F(1, 28) = 8.5$, $p = 0.007$; $\eta^2_p = 0.23$; precession: $F(1, 28) = 61.6$, $p < 0.000001$; $\eta^2_p = 0.69$), but the interaction between the two was not ($F(1, 28) = 1.4$, $p = 0.24$; $\eta^2_p = 0.05$). The hit rates for the younger observers were, on average, 11.0% higher than those for the older observers. With regards to false alarm rates, there were main effects of type of

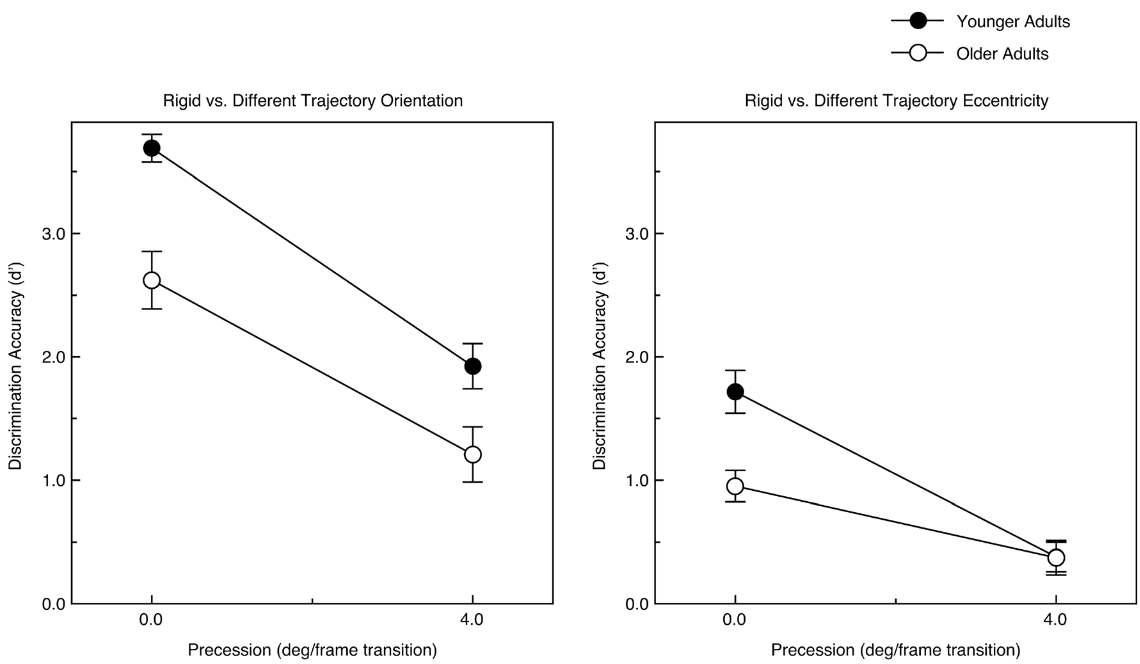

Fig. 4. The younger (filled circles) and older (open circles) observers' discrimination accuracies (d' values) plotted as functions of precession and type of nonrigidity. A d' value of zero represents chance levels of performance, while d' values of 3.5 to 4.0 represent essentially perfect discrimination performance. The error bars indicate ± 1 SE.

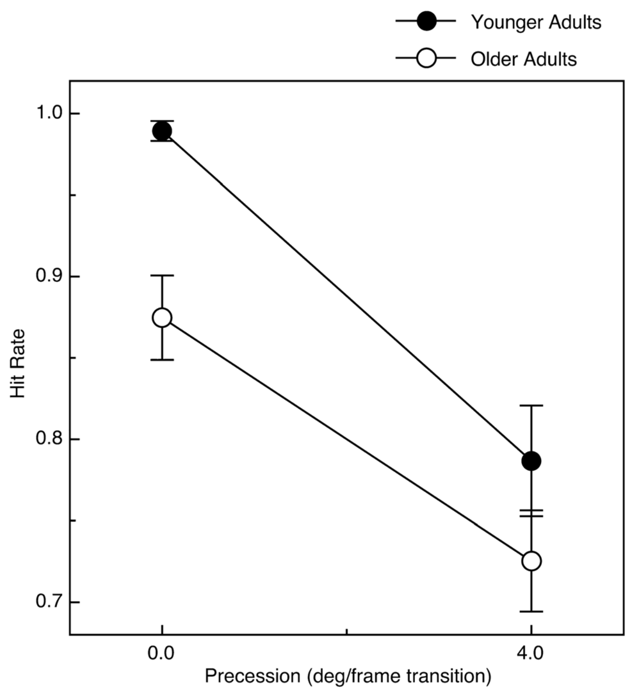

Fig. 5. The younger (filled circles) and older (open circles) observers' hit rates (proportion of the time an observer responded "rigid" when a rigidly moving object was actually presented) plotted as a function of precession. The error bars indicate ± 1 SE.

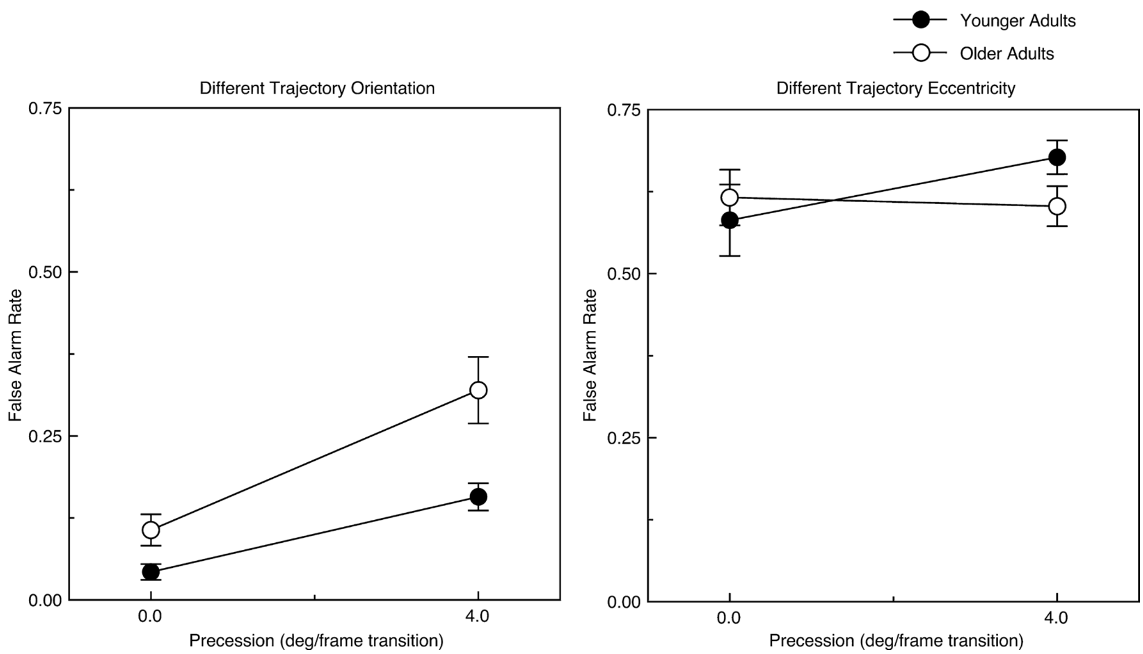

Fig. 6. The younger (filled circles) and older (open circles) observers' false alarm rates (proportion of the time an observer responded "rigid" when a nonrigidly moving object was actually presented) plotted as functions of precession and type of nonrigidity. The error bars indicate ± 1 SE.

nonrigidity and precession (type of nonrigidity: $F(1, 28) = 382.2$, $p < 0.000001$; $\eta^2_p = 0.93$; precession: $F(1, 28) = 14.6$, $p < 0.001$; $\eta^2_p = 0.34$), but not age ($F(1, 28) = 2.5$, $p = 0.12$; $\eta^2_p = 0.08$). There were, however, a number of significant interactions involving age (age × type of nonrigidity: $F(1, 28) = 7.9$, $p < 0.01$; $\eta^2_p = 0.22$; age × type of nonrigidity × precession: $F(1, 28) = 7.0$, $p = 0.013$; $\eta^2_p = 0.20$). One can readily see these interactions involving age in Fig. 6 -- for example, there was a clear effect of age upon false alarm rates for the nonrigid motions with

different trajectory orientation (left panel), but not for the nonrigid motions with different trajectory eccentricity (right panel). Finally, the precession × type of nonrigidity interaction was significant ($F(1, 28) = 9.7$, $p = 0.004$; $\eta^2_p = 0.26$), but the precession × age interaction was not ($F(1, 28) = 0.01$, $p = 0.92$; $\eta^2_p = 0.0$). The precession × type of nonrigidity interaction occurred, because the difference in false alarm rates between the conditions with and without precession was four times larger for the nonrigid motions with different trajectory orientation than for the nonrigid motions with different trajectory eccentricity; this interaction is clearly visible in Fig. 6.

As described earlier, there was a significant overall effect of age upon d' (perceptual sensitivity to the difference between rigid and nonrigid object motion, see Fig. 4). Figure 7 plots d' as a function of chronological age for the older observers. One can readily see that while older adults, as a group, possess lower sensitivity than younger adults, old older adults do not necessarily perform worse on the discrimination task than young older adults. For example, the plot shows that the discrimination performance of a 79 year-old adult was better than that of a 67 year-old. Given the results shown in Fig. 7, it is not surprising that there was no significant correlation between chronological age of the older adults and their ability to discriminate rigid from nonrigid object motion (Pearson $r = -0.274$, $p = 0.32$, 2-tailed). Indeed, variations in chronological age among the older observers only accounted for 7.5% of their variance in d'.

Figure 8 shows overall mean discrimination performance (d' values) for all 30 individual younger and older observers. It is clear that while there is a difference between the overall performance of the younger and older adults (main effect of age upon d' was significant) that the distributions of the younger and older observers overlap extensively. For example, the top seven performing older adults had overall discrimination accuracies that were numerically higher than the younger adults (in their twenties) with the lowest overall d' values. The top three older observers (ages were 72, 77, & 79 years) had overall discrimination accuracies that exceeded the mean performance of the younger observers.

Discussion

The current results demonstrate that aging is associated with a significant decrement in the ability to discriminate rigid and nonrigid motion. This reduction is similar to age-related deteriorations in performance obtained for other motion-related tasks[15–27]. It is important to note, however, that our older adults performed very well in absolute terms and had excellent sensitivity at distinguishing rigid object motion from the nonrigid motions with different trajectory orientation, particularly when there was no precession (which made the task difficult for all observers). In this condition, the average d' value for the older adults was 2.62 (see left panel in Fig. 4), which corresponds to about 90.5% correct[38]. The heterogeneity in overall performance exhibited by the older observers in the current experiment (overall discrimination accuracy varied greatly across individual older observers, from a low d' value of 0.6 to a high d' of 2.3, see Fig. 8) is important to note -- many individual older adults performed better than a substantial portion of individual younger observers. The adverse effect of increased age found in the current experiment is statistically significant, but reflects only an overall difference in performance between the two *groups* of observers and does not necessarily exist for particular individuals. Such heterogeneity in visual performance is not unusual for motion-related tasks. For example, consider Experiment 1 of Norman, Ross, Hawkes, and Long[15]. While there was an overall age-related reduction in the ability to discriminate speed (see Fig. 2 of Norman et al.[15]), there was nevertheless large variation in the discrimination abilities of individual older observers. The individual difference thresholds for the older observers for the fastest standard speed, for

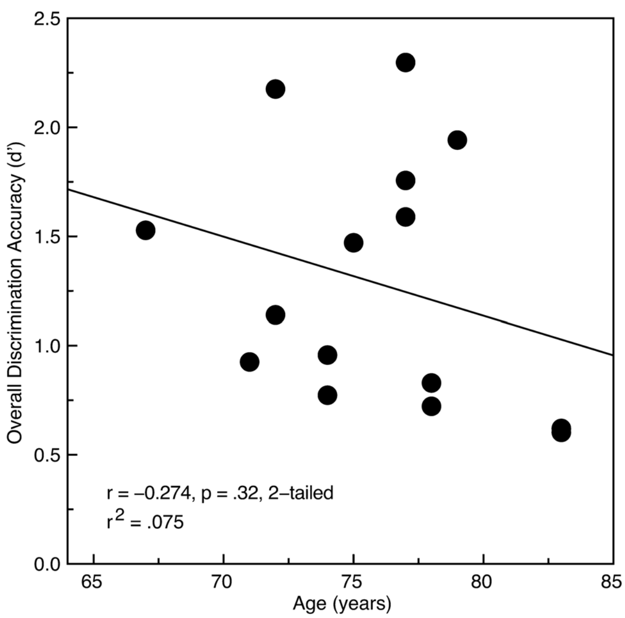

Fig. 7. A plot illustrating d' as a function of chronological age for the older observers. The solid line indicates the best-fitting linear regression.

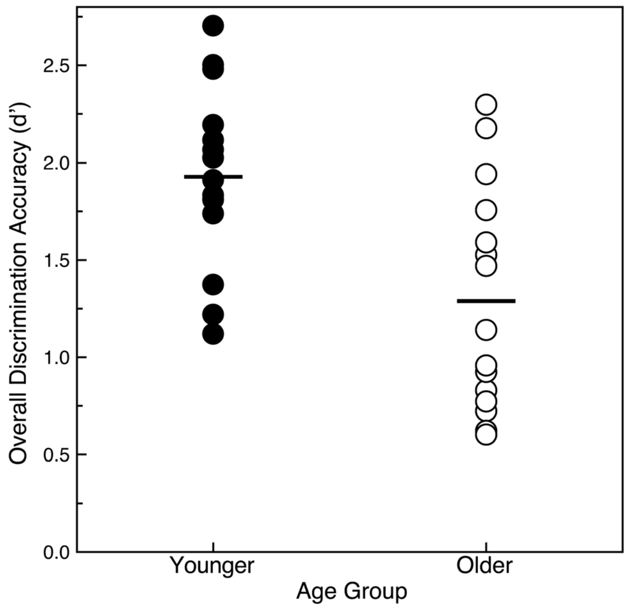

Fig. 8. A plot illustrating overall discrimination performance (d') for both groups of observers. The horizontal line segments indicate the mean performance for each age group.

example, varied from a low of 4.9% to a high of 34.3% (see Fig. 5 of Norman et al.[15]), and these individual variations in speed discrimination performance were unrelated to the specific ages of the individual older observers (i.e., the older old observers did not perform any worse than the younger old observers).

One type of error exhibited by both our younger and older observers is illustrated in Fig. 6. This figure plots the proportion of times that an observer responded "rigid" when the stimulus object was in fact nonrigid. Such errors indicate that nonrigidly moving objects can be perceived as rotating rigidly in depth. Such failures to detect nonrigid motion have been documented before -- for example, see Experiment 1 of Norman and Todd[10] and Experiment 4 of Domini, Caudek, and Proffitt[41]. The current results show (see Fig. 6) that our older observers were more likely than the younger observers to perceive nonrigid objects as rigidly moving, but this only occurred when the object nonrigidity was caused by differences in trajectory orientation (compare the left and right panels of Fig. 6). The opposite type of error also commonly occurred in our experiment, when observers perceived rigidly moving objects as being nonrigid. Consider Fig. 5. Any hit rate less than 1.0 in our experiment indicates that observers sometimes (or frequently) responded "nonrigid" when in fact the object motion was rigid. Past research has frequently demonstrated that rigidly moving objects can indeed be perceived as nonrigid by anyone, including younger adults[33,42–47]. From our current results (shown in Fig. 5), one can see that the older observers perceived rigid objects as being nonrigid more frequently than the younger observers (i.e., the older observers' hit rates were significantly lower). Indeed, the older adults perceived about 27.5% of the rigid objects as being nonrigid when precession was present.

The various results obtained in the current study clearly demonstrate that older adults can effectively perceive rigid and nonrigid object motion in depth (e.g., the distributions of the younger and older observers extensively overlap, see Fig. 8). It is nevertheless true that there are a variety of age effects upon d', hit rate, and false alarm rate (see Figs. 4, 5, 6). Thus, the findings of our current experiment indicate that the previously known age-related deficits in motion perception[5,15–27] extend to the discrimination of rigid and nonrigid object motion.

Previous neurophysiological research conducted upon older and younger rhesus monkeys helps explain the earlier described age-related deficits in performance for basic motion tasks, for example those involving judgments of motion direction and speed[5,15–22]. The single-unit recording studies by Liang et al.[48], Yang, Liang, Li, Wang, and Zhou[49], and Yang, Zhang, et al.[50] all demonstrate that neurons in cortical area MT do not function normally in old monkeys. The study by Liang et al.[48] demonstrated that aging substantially reduces the direction selectivity of MT neurons in monkeys (see Fig. 2 of Liang et al.[48]). Yang, Zhang, et al.[50] found that aging produces a significant degradation of speed selectivity in MT. Such important and consequential age-related abnormalities in neuronal functioning are thought to be caused by a deficit in GABA neurotransmitter activity (see related behavioral studies by Tadin et al.[29] and Betts et al.[28]). For example, Liang et al.[48] indicated (p. 863) that "such hyperactivity and decreased selectivity are thought to be due to the degradation of GABA-mediated inhibition within the visual cortex."

Schmid, Boyaci, and Doerschner[31] conducted an fMRI brain imaging study and presented human participants with a variety of nonrigid object motions (e.g., rippling cloth blown by the wind, waves in fluid, a wobbling elastic cube, a stretching and bouncing elastic cube). In their discussion, Schmid et al. said (p. 6) "Although motion compellingly conveys the properties of non-rigid materials such as stiffness and elasticity... until now the neural basis of non-rigid material motion remained unexplored...regions preferring dynamic dot materials included several areas in occipito-temporal and, -parietal cortices, secondary somatosensory cortex, and premotor

regions." The authors describe this (p. 2) as a "cortical network involved in the perception of non-rigid materials." With regards to our current experiment, it is likely that the age-related deficit in discriminating nonrigid from rigid object motion that we have identified (e.g., Figs. 4 and 8) is due to a deterioration of functioning within this network of extrastriate cortical neurons that prefer nonrigid motion[31].

The current research and results are important—no previous investigation of aging and vision has evaluated the ability of older adults to discriminate between rigid object motion (i.e., rigid rotations in depth) and nonrigid object deformation. It is nevertheless true that the current research is limited in scope and represents only an initial step. At the moment, we do not know what the consequences of reduced discriminability are for older adults in everyday life situations. Does a reduced perceptual sensitivity to nonrigid motion negatively affect the behavior of older adults? The presence of a widespread cortical network in the brain devoted to nonrigid motion[31] strongly suggests that a visual sensitivity to nonrigid motion is indeed important for successful completion of everyday life activities. If this is so, the age-related deterioration in visual nonrigid object perception documented in the current study almost certainly has practical consequences for everyday life. Determining the practical effects of a reduced sensitivity to nonrigid motion will be an important task for future research.

Conclusion

While older adults can often successfully differentiate between rigid and nonrigid object motion (e.g., overall d' value in the best condition was 2.62), their discrimination performance is nevertheless substantially lower than that exhibited by younger adults. This overall decrease in sensitivity is caused by both reductions in hit rate (lower likelihood of detecting rigid object motion) and increases in false alarm rate (failing to detect nonrigid object motion as nonrigid).

Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Author contributions

J.F.N. developed the study concept and design. J.F.N. was responsible for stimulus generation and preparation. Data collection was performed by J.F.N., A.B.R., E.N.B., P.A., A.M.B., H.P., and R.D.P. The data analysis was performed by J.F.N. The figure preparation was performed by J.F.N. J.F.N. wrote the manuscript. All authors reviewed the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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